Clinical carboxymetry; measuring carbon dioxide in respiratory gases and in blood

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SUMMARY

CHAPTER I

After some introductory remarks on the development of carbon dioxide measurement, five practical methods for the determination of the arterial pCO_2 are reviewed.

1. By solution of the HENDERSON-HASSELBALCH equation.
2. By use of interpolation methods.
3. By direct electrometric measurement.
4. By microtonometry.
5. By rebreathing techniques.

The estimation of the arterial pCO_2 by the measurement of end-tidal or average expiratory CO_2 is discussed next. A survey of methods and instruments for the measurement of CO_2 in gases is presented. Many of these methods are not specific for CO_2 and only a few are applicable in clinical practice.

A new instrument, the cediometer, for the continuous measurement of CO_2 in respiratory gases and accurate determination of the total CO_2 content in blood or plasma is introduced.

CHAPTER II

In this chapter some fundamentals of carbon dioxide chemistry are reviewed. Some data on the solubility of CO_2 in aqueous solutions are given. Next, the reversible hydration of carbon dioxide and the ionization of carbonic acid are described. Special attention is given to the relationship between K_1 and K_1', the *true* and *apparent* ionization constants of carbonic acid. Furthermore, the rates of the hydration and dehydration reactions are considered with some of the biological implications.

CHAPTER III

This chapter deals with the theory of the photometric determination of carbon dioxide, using an acid-base indicator. The principle of this method was introduced in 1952 by BRINKMAN and LAMBERTS, who designed an instrument for the continuous measurement of the CO_2 content of average expiratory air in anaesthetized patients.

For a quick photometric determination of the CO_2 content of gases two conditions must be fulfilled. First, the reactions involved in the uptake of carbon dioxide by the indicator solution should be fast and reversible. Secondly, there should be enough sensitivity *i.e.* a sufficient change of light absorption within the measuring range of 0-10 vol.% CO_2. A $NaHCO_3$-BTB (bromthymolblue) solution, having a concentration of 5.95 mmoles/l $NaHCO_3$ and 0.08 mmoles/l BTB, proved to be suitable.

The behaviour of the $NaHCO_3$-CO_2-BTB system has been thoroughly investigated. The absorption spectra of BTB (fig. 3) indicate that measuring the colour change of the indicator should preferably be done in red light. Photometry of the indicator solution, under conditions where LAMBERT-BEER's law strictly holds, yields a non-linear relationship between CO_2 content and light transmission (T) of the solution. By employing a rather broad band of red light, a certain degree of controlled deviation from LAMBERT-BEER's law is introduced, resulting in a linear CO_2/T relationship.

CHAPTER IV

An 'absolute' photometric measurement of CO_2, based on the principles outlined in chapter III, is practically impossible because of two factors: (1) the use of filter photometry instead of spectrophotometry; (2) the use of an indicator of which the extinction coefficient is not known exactly. To overcome these difficulties calibration, using samples with a known CO_2 content, is necessary.

To simplify the necessary recalibrations, photometry at the isobestic point of BTB (501 mμ) was introduced. At this wavelength the transmission of the indicator solution is dependent only on the total concentration of BTB and independent of the CO_2 content of the solution.

An experimental photometer, equipped with an Ilford 281 red

filter and a Schott blue interference filter ($\lambda \approx 501$ mμ) is described. The sensitivity adjustment of this photometer is coupled to the measurement in blue light (position (a), fig. 15). In position (b) the 'blue' photocell is connected, reversed in parallel, to the 'red' cell. This position serves for the adjustment of the zero point of the CO_2 measurement (compensation) and for the actual measurement itself.

CHAPTER V

A detailed description of the cediometer is given in this chapter. In the measurement of respiratory CO_2, sampling, transport and analysis of the gas are combined. A sample of respiratory air is drawn directly through the indicator solution by means of a pump. The operation principle of the cediometer is shown in fig. 17. The instrument contains a built-in sampling control unit, which serves to select particular phases of the breathing cycle.

For the measurement of the total CO_2 content in blood or plasma, carbon dioxide is set free from the sample by acidification in a blood cell, which forms a closed circuit with the pump and the photometer cuvette (fig. 27).

The instrument consists of a switchbox and a photometerbox. Fig. 16 shows the complete apparatus for measuring CO_2 in respiratory gases, fig. 29 the set-up for measuring CO_2 in blood or plasma.

CHAPTER VI

Following a description of the operation procedure for the continuous measurement of the CO_2 content of average expiratory and end-tidal air with the cediometer, attention is paid to the calibration of the instrument and the acquiring of optimal response time by use of appropriate gas sampling techniques.

The use of silicone grease, necessary to prevent foaming of the indicator solution, results in a slight decrease of total BTB concentration after some time. Due to a rise in temperature of the indicator solution, when patient's air is led through it, a slight error in the measurement is also introduced. The concentration and temperature effects, however, counteract each other in part; the resulting error is but slight and can easily be avoided by periodic recalibration.

The accuracy of the cediometer has been investigated by

simultaneous measurements of the CO_2 content of a large number of gas samples, using the HALDANE apparatus and an infrared analyser as control instruments (figs. 34, 35, 36). A mean difference of + 0.01 vol.% CO_2 with a standard deviation of 0.18 vol.% was found in a series of 51 gas mixtures, compared with the HALDANE technique. In comparing the cediometer method with the results found using an infrared analyser, the mean difference was + 0.02 vol.% CO_2 with a standard deviation of 0.17 vol.% for a series of 28 gas mixtures.

In another series of experiments, the effectivity of the built-in end-tidal sampler was tested. The end-tidal $\not pCO_2$ values measured by the cediometer reached, on the average, 96% of the peak concentration of each respiratory cycle as indicated by an infrared analyser.

CHAPTER VII

The first part of this chapter gives the operation procedure for the determination of the total CO_2 content in plasma or whole blood with the cediometer, with special attention paid to the handling of the samples. Only 0.5 ml of a sample is required and a complete determination takes not more than 6 min.

The CO_2/T relationship and the composition of the indicator solution are highly interdependent. Experimentally it was found that a $NaHCO_3$-BTB solution with a concentration of 5.95 mmoles/l $NaHCO_3$ and 0.04 mmoles/l BTB, fulfils the requirements of sensitivity and of linearity of the CO_2/T relationship within the measuring range of 0-45 mmoles/l CO_2 content.

To check the accuracy and reliability of the method, control experiments were performed under various conditions, covering a total of 224 blood samples. The VAN SLYKE's manometric technique was used for the determination of the control samples. The results of these experiments are presented in table X (p. 85) and table XI (p. 85). A very satisfactory accuracy of the cediometer method was found.

CHAPTER VIII

In this chapter some clinical applications of the cediometer are described. The description is elucidated by a number of case

reports on the continuous observation of expiratory CO_2 in anaesthetized patients. A complete clinical interpretation of the curves obtained was not intended to be given, however some comments are presented.

The calculation of the arterial pCO_2 from pH and total CO_2 content of plasma or whole blood is also discussed. Special attention is paid to the SINGER-HASTINGS nomogram as an aid in calculating pCO_2 from pH and whole blood CO_2 content.